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Road grade influence on the exhaust emissions of a scooter fuelled with bioethanol/gasoline blends

Maria Vittoria Prati, Maria Antonietta Costagliola*, Chiara Tommasino, Livia Della Ragione, Giovanni Meccariello

Istituto Motori of National Research Council, viale Marconi, 4 – 80125 – Napoli (Italy)

Abstract

Recently, the International Agency for Research on Cancer has assessed evidence that exposure to outdoor air pollution causes lung cancer and increases the risk of bladder cancer. Because air pollution in urban areas is mainly caused by transportation, it is necessary to evaluate pollutant exhaust emissions from vehicles and scooters during their real-world use. Laboratory tests, with the exception of the high repeatability of the results, often cannot explain the influence of some parameters, such as ambient conditions, traffic congestion, and road gradients. Therefore, experiments were conducted to study the effects of road gradients on the exhaust emissions of a medium displacement scooter, which represents a very popular means of travel in Southern Italy. First, the scooter was instrumented with a global positioning system (GPS) to acquire speed profiles and positions in an urban route of Napoli city, which is characterized by significant changes in the road gradient. The velocity profile has several missing points due to GPS signal loss over some stretches of road adjacent to tall buildings. The road gradient values were built into an algorithm to synchronize the missing data through Google elevation API based on a model of the same path with a complete set of data. Afterwards, some representative slope values for each kinematic sequence/driving cycle were evaluated. These new variables were found to contribute to the individual real-world driving cycles. The resulting real-world driving cycle was tested using a chassis-dynamometer to continuously simulate the exact road gradient. A series of experiments with and without the road gradient simulations were performed to evaluate the influence of the road gradient on the exhaust emissions of carbon monoxide, total hydrocarbons, nitrogen oxides, and carbon dioxide. This analysis was performed using a two-wheeler vehicle fuelled with commercial gasoline and two blends with a maximum bioethanol content of 20% vol. Gaseous emissions were correlated to the vehicle specific power (VSP), which is the most useful parameter for addressing the road gradient together with the kinematic characteristics of the driving cycle and the vehicle characteristics. Through a multivariate statistical approach, this type of gradient analysis can permit correlation of the emission profiles for a specific road position, and evaluate its influence on their

* Corresponding author. Tel.: +39-081-717-721-0; fax: +39-081-239-609-7.
E-mail address: m.a.costagliola@im.cnr.it

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behavior. A strict dependence on carbon dioxide emissions and fuel consumption exists for the VSP. The road gradient greatly increases the vehicle power demands, resulting in an increasing amount of fuel consumed for each kilometer driven.

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Keywords: Real-world driving cycle; road gradient; scooter emissions; vehicle specific power; bioethanol gasoline blend.

1. Introduction

Recently, the International Agency for Research on Cancer has assessed evidence that exposure to outdoor air pollution causes lung cancer and increases the risk of bladder cancer (IARC, 2013). Transportation is the predominant anthropogenic source of outdoor air pollution. A reliable assessment of the contribution of vehicle exhaust emissions to the urban air quality requires knowledge on the real-world emission behaviour of in-use vehicles. Recently, a new approach to measure vehicle exhaust emissions was investigated (Franco et al., 2013). This approach involves emission measurements during real-world driving using portable emission measurement systems (PEMS) (Kousoulidou et al., 2013,). Unlike laboratory tests, this method offers the capability to address the influence of kinematic and ambient parameters on emissions and fuel consumption, such as traffic congestion, road grade, and the ambient temperature. However, the main disadvantage of this method is the difficulties in achieving pure repeatability due to un-controlled factors during the experimental tests, such as the road traffic. Several papers have reported the experimental results of real-world fuel efficiency and emissions from light-duty vehicles and passenger cars (Huang et al., 2013, Weiss et al., 2012, Liu et al., 2011). Some of these correlate exhaust emissions to road traffic, highlighting the need to improve urban traffic planning to mitigate air pollutant emissions (Hu et al., 2012, Rolima et al., 2014). In urban transportation, an important part of preserving the air quality is to ensure emissions from two-wheeler vehicles are minimized. In fact, these vehicles are widely used for short trips in urban areas in Mediterranean cities, and contribute greatly to air pollution. Therefore, applying this new approach to emission measurements is becoming more and more necessary to evaluate the contribution of transportation on urban air quality. However, very few studies address the influence of road grade on light-duty vehicle exhaust emissions (Frey H.C. et al., 2008, Wyatt, D et al., 2013). From a general perspective, the grade of a road can increase or decrease the frictional resistance that a vehicle has to overcome, thus influencing both vehicle emissions and fuel consumption.

In this work, the experimental research focuses on the real-world emission behavior of a two-wheeled vehicle. The exhaust emissions of a Euro 3 scooter were correlated with real-world driving, in particular, urban traffic and road gradients. With this goal in mind, a monitoring campaign was conducted to acquire speed traces along two urban routes of Napoli city, which are characterized by different orographies. The speed traces, reflecting the real traffic situations on the trips, were repeated using a chassis dynamometer to simulate the vehicle inertia and road load resistance, including that derived from the road gradient patterns. Exhaust emissions were correlated to the vehicle driving, which was estimated using the VSP parameter (Vehicle Specific Power), which is dependent on the vehicle speed, acceleration and the road gradient (Boroujeni & Frey, 2014). This study was conducted using commercial gasoline and bioethanol/gasoline blends containing a maximum alcohol content of 20% vol.

2. Materials and methods

2.1. Vehicle and fuels

A Euro 3 scooter with an engine displacement of 125 cm^3 was tested. The fuel injection system for this scooter involves a carburetor and an exhaust duct equipped with a catalyst for pollutant abatement.

The tested vehicle used three fuels: a commercial gasoline (E0), a bioethanol/gasoline with a 10/90% vol. blend (G10) and a bioethanol/gasoline with a 20/80% vol. blend (G20). The G10 and G20 blends were prepared starting with a special oxygen free gasoline to exactly control the ethanol content and comply with standard limits on the fuel vapor pressure (Directive 2009/30/EC). Bioethanol, obtained from grape pomace produced during traditional wine processing, was provided by I.M.A. srl (Trapani, Italy). Some fuel properties are reported in Seggiani M. et al. 2012. The choice of ethanol content in the fuel blends allows an investigation on the fuel using a medium alcohol content (G10) and a high alcohol content (G20). Both bioethanol blends were tested without any engine modifications.

2.2. Real driving cycles

To acquire the real speed patterns, the test vehicle was instrumented with a Global Position System (GPS) and driven along two urban routes in Napoli city. In this way, both the speed profile and road altitude were continuously monitored during real-world use.

The two routes are characterized by different orographies. The route Napoli_1 is flat, whereas Napoli_2 is characterized by large road gradients covering downhill and uphill portions. Figure 1 shows the speed profiles and the elevation of the two driving cycles as a function of the travelled distance. Napoli_1 is almost 14 km in length, and the average speed achieved by the scooter is 30.2 km/h. Napoli_2 is almost 6 km in length, and the average speed achieved by the scooter is 19.8 km/h. Figure 1 highlights that Napoli_1 covers a route characterized by small changes in elevation, which ranges between 8 to 20 m. However, the road gradient of Napoli_2 is characterized by an average positive gradient of almost 3.5% with the maximum values reaching 8% in some cases. Additionally, the downhill the average negative gradient is almost -3.4%.

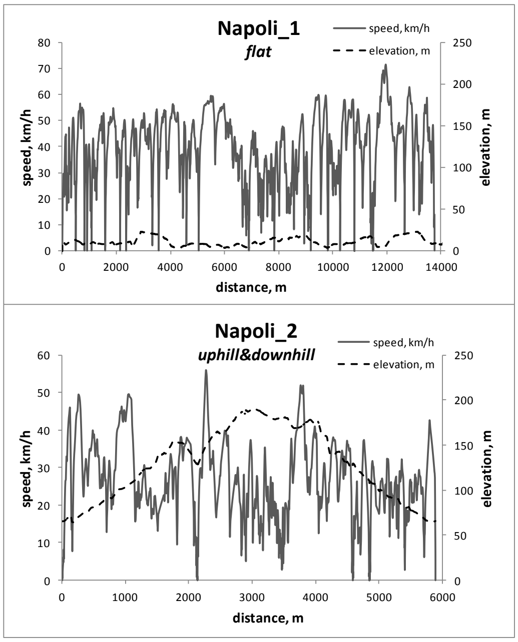

Fig. 1. Speed profiles and elevation of the Napoli_1 and Napoli_2 driving cycles as a function of distance.

2.3. Chassis-dynamometer tests for pollutant measurements

The real-world driving cycles were examined using a chassis-dynamometer to simulate the second-by-second road load resistance, vehicle inertia and road gradient. The rollers are connected to an electric brake/engine, which offers the proper driving resistance to the vehicle (based on the sum of the road load, inertia, and road grade). The driving cycles were executed after a vehicle warming for not encountering cold start period. A variable speed fan was positioned in front of the vehicle to provide cooling air. During execution of driving cycles, the exhaust flow was diverted to a constant volume dilution system and diluted with ambient air. A stream of diluted exhaust was sampled and continuously analyzed to measure the concentrations of carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NO_x) and carbon dioxide (CO_2) in the exhaust. At the same time, another stream was used to fill Tedlar bags over the entire driving cycle. The bags were analyzed after the tests for obtain the average concentration of each pollutant. The volumetric concentrations were converted to emissions throughout the exhaust and dilution air flow rates. Additionally, the fuel consumption was estimated by applying a carbon balance on the exhaust species. A detailed description of experimental apparatus is reported on in Seggiani M. et al. 2012.

2.4. Vehicle Specific Power (VSP)

The VSP (Vehicle Specific Power) parameter is widely used to account for the full vehicle load to explain the exhaust emissions. The formula for the VSP calculation (kW/ton) is (Frey et al., 2006):

$$VSP = v[(1-\varepsilon)a + g(r/100 + C_R)] + 1/2\rho_{AIR}v^3\,(C_D\,A/m) \qquad (1)$$

Where a: vehicle acceleration [m/s^2], v: vehicle speed [m/s], ε: factor accounting for rotational masses, g: acceleration of gravity [m/s^2], C_R: rolling resistance coefficient, ρ_{AIR}: ambient air density [kg/m^3], C_D: aerodynamic drag coefficient, A: vehicle frontal area [m^2], m: vehicle mass [ton], r: road grade [%].

According to a consolidated approach, the vehicle driving can be categorized into 14 VSP bins. Bins 1 and 2 include negative VSP values, which correspond to the vehicle decelerating, a negative road grade (downhill) or both. Bin 3 includes vehicle idling. Bins 4 to 14 include positive values and occur during cruising, acceleration, and uphill travel.

During this experimental activity, the VSP was calculated second-by-second using the vehicle speed, acceleration, and road grade. Subsequently, the gaseous pollutant emissions and fuel consumption were related to the VSP values and grouped according the different bin classifications.

3. Results

3.1. Influence of the bioethanol content in the fuel

The initial analysis was conducted to investigate the emissions behaviour of the scooter when varying the fuel. In this section, the experimental results of the entire real-world driving cycles are presented. The influence of the road grade is investigated in the next section. Figure 2 shows the pollutant emissions in g/km relative to the E0, G10, and G20 fuels. The data includes the average of two repetitions of Napoli_1 and Napoli_2 cycles, the latter executed with and without the road grade simulation (indicated in the figure by the flat and slope, respectively). The error bars account for the standard deviation associated with the mean value.

A large reduction in CO and THC is visible when the bioethanol/gasoline blends are used. In particular, CO and THC emissions measured when the G10 blend is used are 40-70% lower than those measured for the E0. The G20 did not show any improvement in emissions compared with the G10, with the exception of the CO on the Napoli_1 cycle. However, THC emissions during the Napoli_2 cycle increased from G10 to G20. This indicates poorer combustion due to an excessive amount of leanness in the air fuel mixture. The experimental tests were conducted using the oxygenated fuels without any engine adjustments. The poor combustion of the G20 fuel compared with the E0 does not produce higher CO and THC emissions because the oxygen content aids the oxidation of such compounds over the three-way catalyst. A further effect of the G20 is a slight decrease in the amount of NO_x produced. This is the result of the low peak temperature reached inside the engine when poorer quality combustion occurs (Karavalakis et al., 2012).

Despite the lower carbon content of the bioethanol blends compared with gasoline, the CO_2 emissions increased when using the G10 and G20 blends (see Fig. 3). In this case, the positive effects related to the fuel chemical composition are mitigated by the enrichment demands from the engine (Costagliola et al., 2013). The major fuel consumption of the G10 and G20 blends is clearly visible in Fig. 4 on the right side. Using the G10 fuel blend increases the volumetric fuel consumption between 3-10%. This percentage further increases to 5-15% for the G20 fuel blend.

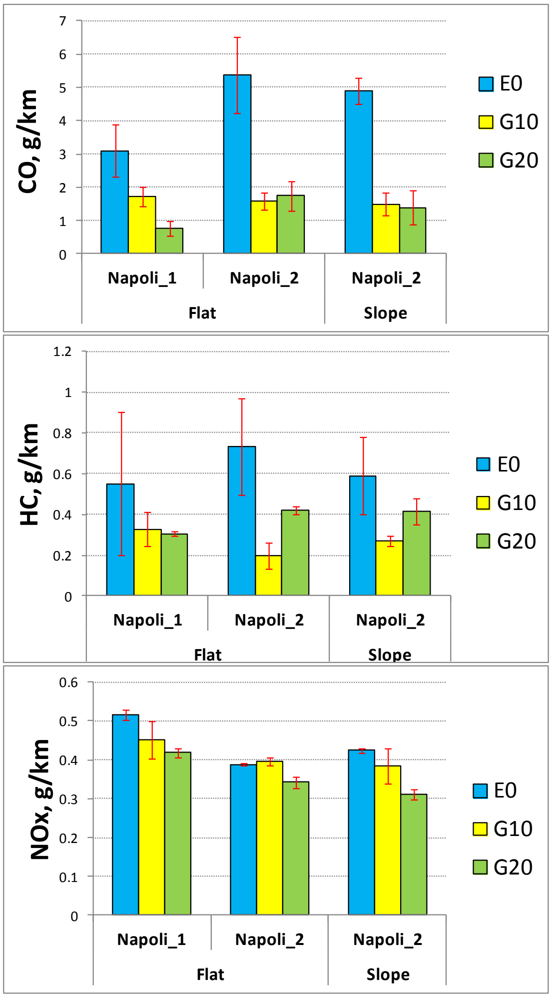

Fig. 2. CO, THC, NO_x emissions from the tested fuels

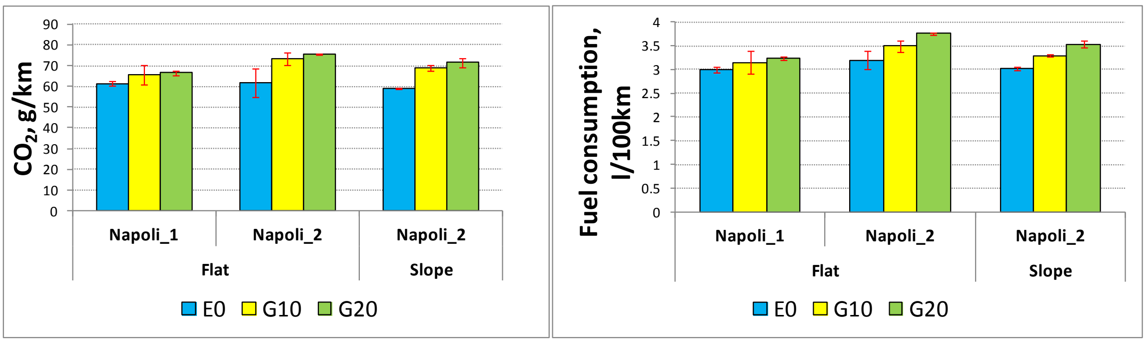

Fig. 3. CO_2 and fuel consumption for the tested fuels

3.2. Road grade influence

The analysis of the full driving cycles, presented in section 3.1, does not highlight any significant differences between the Napoli_2_flat and Napoli_2_slope. This two driving cycles have the same speed vs. time trace, but were performed with and without road grade simulations on the chassis- dynamometer. The increasing road grade implies that the engine has to provide greater power to maintain the scooter at a constant speed. This requires greater fuel consumption, which results in higher CO_2 emissions. In situations with a negative gradient, the force of gravity accelerates the scooter and leads to an overall reduction in its fuel consumption. The influence of the road gradient on the exhaust emissions is not visible throughout the entire driving cycle because it corresponds to a closed real pattern (i.e., the starting and the ending points coincide), and thus includes uphill and downhill components. The presence of both positive and negative grades along the same route has the effect of balancing these opposite influences on engine performance.

To more thoroughly investigate the influence of the road grade, the Napoli_2 cycle was separated in two parts to account for the positive and negative grades, respectively. The emissions measured over these two tracts were compared with the presence and absence of the road grade in the simulation. Figure 4 shows the results of this analysis for CO, THC, and NO_x and CO_2 emissions. Generally, the positive road grade simulation yields higher emissions and the negative road grade simulation results in lower emissions. This observation is confirmed for NO_x and CO_2 emissions, which are directly influenced by the engine power demanded. The CO and THC are less influenced by the road gradient due to the high variability of the data and also the strong effect of the pollutant abatement mechanisms in the exhaust catalyst system.

Table 1 summarizes the mean percentage variations in the CO, THC, and NO_x and CO_2 emissions due to the road grade simulation. The table also highlights differences that are significant at a 95% confidence interval. Major differences are seen for the negative road grade. The decrease in emissions over the downhill tract is greater than the increase during the uphill tract. The highest percentage variations measured are for the NO_x, which sees a greater than 60% emission reduction on the negative slope tract. Increases are observed for the CO_2 and the fuel consumption variations (higher than 12%), for the uphill tract in the Napoli_cycle. However, the negative road grade led to a reduction in emissions of almost 30%.

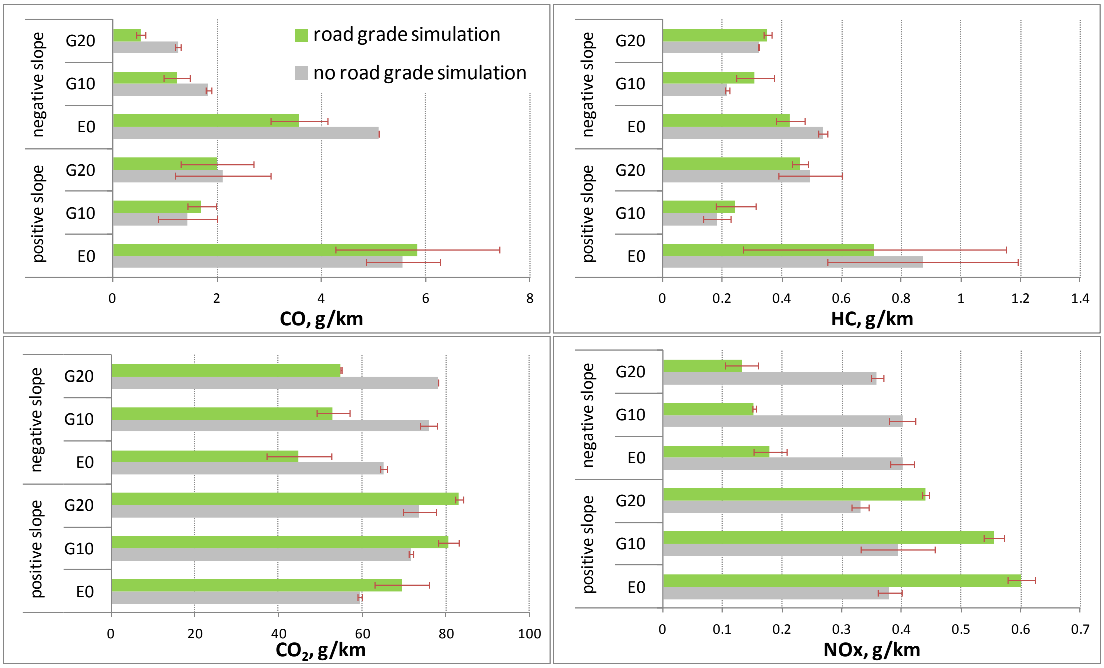

Fig. 4. Comparison between emissions obtained with and without the road grade simulation

The scooter behaviour is affected by the different road grade but does not change for the different fuels. The bioethanol content strongly influences the emissions, but not the variations due to the road grade simulations.

Table 1. Emission percentage variation due to the road grade simulation (*significant difference at the 95% confidence interval)

		Positive grade	Negative grade
CO	E0	5.1	-30.2
	G10	18.8	-33.1
	G20	-5.3	-57.1*
THC	E0	-18.7	-20.2
	G10	34.4	43.1
	G20	-6.9	9.3
NOx	E0	58.3*	-55.5*
	G10	41.1	-62.1*
	G20	33.2*	-63.2*
CO_2	E0	16.8	-31.2
	G10	12.4*	-30.2*
	G20	13.1	-29.8*

3.3. VSP analysis

To thoroughly analyze the effect that road slope has on emissions, an analysis of the Vehicle Specific Power (VSP) was conducted.

First, the VSP distribution was calculated using the vehicle speed, acceleration, and road grade. Figure 5 shows the cumulative VSP frequency distribution according to the VSP bins. This figure compares the distributions obtained for the same real driving cycle (Napoli_2) executed on a chassis dynamometer without road grade simulations (flat) and simulating the real road grade (slope). The data refers to tests performed with commercial gasoline, E0. The curve shapes highlight the contribution of the road altitude variations on the total vehicle power demanded. When the same speed trace is analyzed by simulating the road grade, a major number of negative VSPs are present due to the contribution of the negative road gradient. Moreover, for the same conditions in the uphill simulation (positive road gradient), the VSP values reach higher values.

The same VSP distribution was observed for both the G10 and G20 fuel blends.

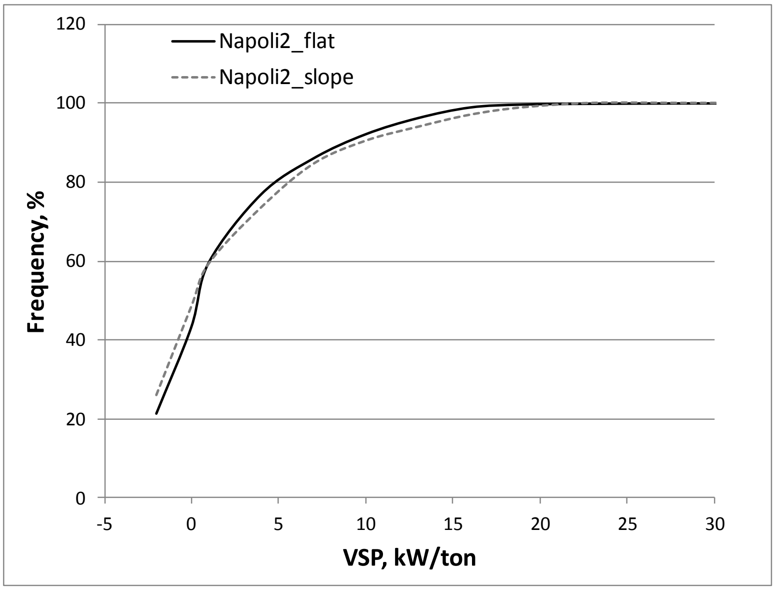

Fig. 5. VSP frequency distribution over the Napoli2_flat and Napoli2_slope routes (E0 fuel)

A common way to analyze the vehicle power influence on the exhaust emissions is to correlate the latter with the VSP bins. Figure 6 shows the results from this analysis. For brevity, only data referring to the E0 fuel will be presented. It is noted the same trends and observations are valid for the other fuels tested.

The NO_x, THC, CO and CO_2 emission rates, expressed as g/s, are determined for the Napoli_1 and Napoli_2 routes executed with and without the road grade simulation (slope and flat, respectively). The comparison between the two flat routes executed with E0 confirms that the NO_x emissions for Napoli_1 are significantly higher than from Napoli_2. Regarding the slope simulations, the Napoli_2 slope emissions are lower than those from Napoli_2 flat, which correlate to the negative VSP. Correspondingly, the slope emissions are higher for positive VSPs. Bins 1 and 2 include negative road gradient, whereas positive gradients are seen in the positive bins. Bin 3 yields the lowest emission values because it includes the idling period.

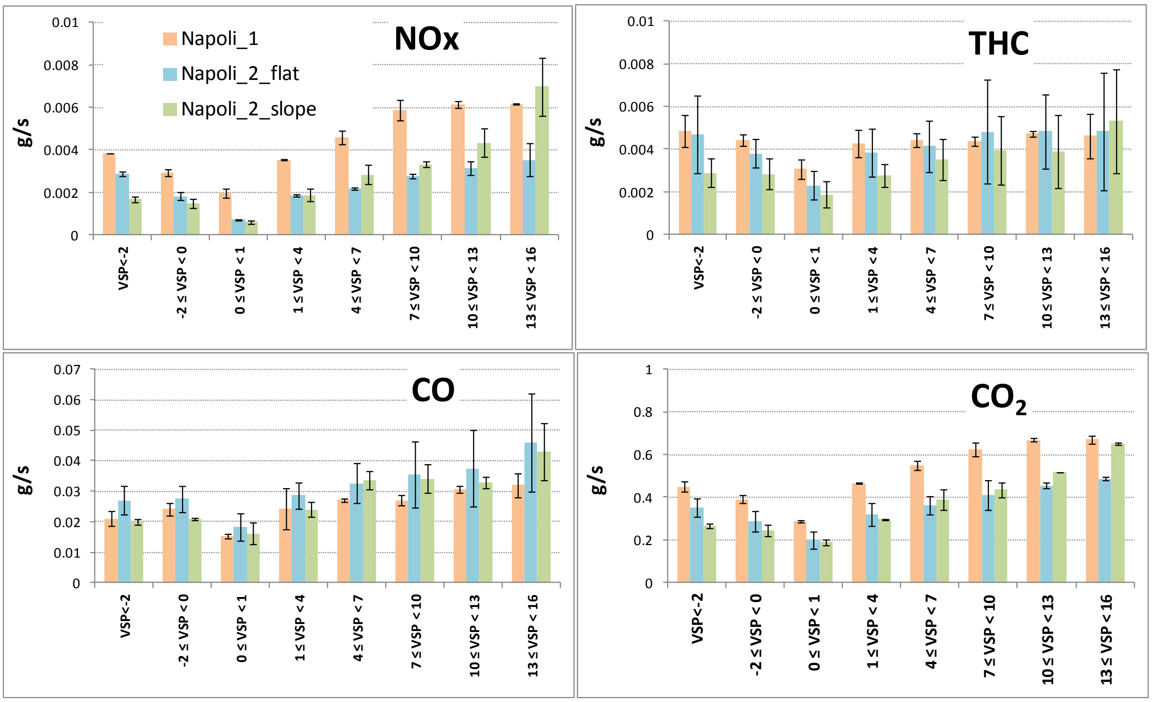

Fig. 6. NOx, THC, CO and CO_2 emissions as a function of the VSP bins (E0 fuel)

Again, we see strong differences due to the road altitude variations for the NOx and CO_2 emissions. The CO and THC emissions are less influenced by such parameters, likely due to the oxidation process occurring over the pollutant abating three-way catalyst.

4. Conclusion

In this work, a Euro 3 scooter was instrumented with a GPS to measure real-world speed and road altitude along two urban routes in Napoli city. The acquired speed profiles were used to simulate the effect of the road grade. The influence of the road grade simulation on the exhaust emissions was investigated using chassis-dynamometer tests performed with commercial gasoline and bioethanol/gasoline blends (up to 20% vol. bioethanol).

Although the use of bioethanol involves a reduction in products that are characteristic of an incomplete combustion process (CO and THC), poorer quality combustion was observed for the highest percentage of bioethanol due to the lean air to fuel ratio. As a consequence, greater fuel consumption is needed to ensure the same power is delivered for a smaller amount of gasoline. In terms of the exhaust emissions, the CO_2 and NO_x emissions increased with the bioethanol content.

Fuel composition does not influence the emission behavior of the scooter when the road grade is simulated. Additionally, the type of fuel does not affect emissions. Positive road grade simulations yield an increase in emissions, and negative road grades lead to reductions in emissions. Generally, for the scooter tested in this work, the benefits from running downhill are greater than the increase in emissions resulting from driving uphill. These observations are confirmed by the VSP analysis.

In addition, a statistical analysis is presently in progress to identify representative variables that can correlate the kinematic values, emissions, and road gradient for each kinematic sequence to better evaluate the effect of the slope.

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